HEAT-SHIELD MATERIALS DEVELOPMENT FOR VOYAGER

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SUMMARY

The moderate entry heating environment predicted for out-of-orbit entries into the Mars' atmosphere has led to the development of new ablation materials with densities less than 350 kg/m^3. These new materials along with previously available denser materials are being evaluated for their application to Mars-entry vehicles of the type proposed for Voyager. Initial evaluations, the results of which are presented herein, include ablative performance in simulated entry environments, RF transmission loss through thermally degraded material, and flexibility at low temperatures following sterilization and vacuum exposure. Most materials tested retained some flexibility to temperatures as low as -100°C. At -130°C, however, most materials exhibited brittle behavior. Several low density filled silicones demonstrated good thermal performance, but only two materials (which are not highly efficient thermally) had acceptable RF transmission for conditions of these tests.

INTRODUCTION

Man's long-time ambition to explore the solar system will be one step closer to reality when scientific instruments are soft landed on the surface of Mars. One mode of entry currently being considered for a Voyager-Mars mission is shown in figure 1. Following the transit from Earth to Mars, the interplanetary vehicle would be placed in orbit about the planet. At the proper time, an entry capsule, shown here as a spherically blunted cone, would be released and placed on a trajectory toward the planet. This type of entry is commonly called the out-of orbit mode. An aeroshell covered with ablation material would protect the payload during entry and provide deceleration of the capsule to the point where the payload could be removed from the aeroshell and soft landed on the planet.

Based on the currently accepted models of the Mars' atmosphere, an entry into Mars poses a very nominal entry heating problem. This is due largely to the low orbital velocity about Mars - about 1/2 the orbital velocity for Earth. Figure 2 shows the stagnation point heat pulse and dynamic pressure calculated for an entry from orbit into Mars for two postulated atmospheres - labeled "VM-7" and "VM-8." For comparison, the entry conditions for Gemini are also shown. The heating shown for Gemini is typical for an out-of-orbit entry into the Earth's atmosphere. An entry into atmosphere VM-8 produces the highest stagnation-point heating-rate and pressure loads for the atmospheres currently postulated, but this is about half that for Gemini. Entry into atmosphere VM-7 produces the highest total heat load, but this is less than 1/5 that of the Gemini heat pulse. The pressure loading on a vehicle entering the Mars' atmosphere is also substantially less than that for an Earth-orbital entry vehicle. Because of the mild heating environment associated with a Mars entry, existing materials, for example, the Gemini heat-shield material, would easily satisfy the heat shield requirements. Such materials, however, are inefficient at these low heating rates. The development of materials particularly suited to the Mars-entry environment offers substantial weight saving potential.

Heat shields for planetary entry vehicles are exposed to some new environments, however, that do require special consideration. Some of these are:

1. Prelaunch sterilization
2. Long space exposure
3. Low temperature
4. Unknown entry environment

In addition, heat-shield designers cannot lose sight of the fact that the prime purpose of planetary exploration missions is to learn more about the planets and, therefore, the heat shield cannot interfere with other devices such as pressure sensors, gas samplers, and radar altimeters.

The purpose of this paper is to present the results of three types of tests conducted on currently available materials in order to determine their suitability for use on a Mars-entry capsule. The tests performed were ablative performance and radio transmission transparency under simulated Mars-entry conditions and material embrittlement at low temperatures in vacuum.

DISCUSSION

An initial screening to determine the ablative performance of 23 materials was conducted at the Ames Research Center earlier this year and the results are presented in reference 1. The materials tested at Ames represented a good cross section of commercial materials available at the time the program was initiated. On the basis of the Ames test results, certain materials were selected to undergo the radio transmission and low-temperature vacuum tests. A second round of ablation tests was performed recently at the Langley Research Center and included some new low-density materials not included in the Ames tests.

In the figures and discussion that follow, the materials are referred to by letter designations. In table 1, the materials are described with respect to their density, base resin system, and their principal fillers.

RF Transmission Tests

Some proposed modes of entry of capsules into the Mars' atmosphere require a radar system which transmits through the heat shield. In order to determine the transmission properties of some typical heat-shield materials, eleven materials representative of several types of ablation material were evaluated under simulated entry conditions in a plasma-arc tunnel. The test configuration used is shown in figure 3. A horn-type transmitting antenna was located within a water-cooled, wedge-shaped model. Ablation material about 1 cm thick formed part of one face of the wedge and was bonded to a metal substrate which was not cooled. The substrate had a cut-out at the antenna location. A receiving horn was positioned within the arc tunnel test section just outside the plasma stream. The transmitted signal was monitored during the test and for four minutes immediately after the arc was turned off.

The test conditions used are given in table 2. A summary of the test results is given in figure 4. The transmission loss in decibels is shown in the form of bar graphs for each of the materials tested at two heating rates. The first solid bar represents a measurement made through the virgin material in an anechoic chamber prior to the tests. The first cross hatch bar is a measurement made in the arc tunnel test section immediately after the arc was turned off and the material was still hot. The second cross hatch bar indicates a measurement made four minutes later after the material had cooled. The last solid bar in each set is a measurement made after the specimen was removed from the test section and again placed in the anechoic chamber. The measurement labeled "cold" and the post-test anechoic chamber measurement would be expected to be about the same. The differences are generally not too significant and can be attributed to changes in the material as it continued to cool and to the less-than-ideal conditions under which the in-tunnel measurements were made. It is apparent from this figure that most of the materials greatly attenuate the signal. Two of the materials tested - material D and material H, showed acceptable performance at the low heating-rate conditions. Material H is a foamed Teflon with a density of 750 kg/m^3. Teflon is known to be a good RF window. The Teflon was was not tested at the higher heating-rate condition. Although material D showed a slightly higher transmission loss just after the high heating-rate test, its transmission loss after 4 minutes was again considered acceptable. No firm criteria have been established for an acceptable RF transmission loss for Voyager, but it should be remembered that a 3 decibel loss represents a 50 percent drop in power. Therefore, based on present concepts it appears desirable to keep the one-way transmission loss below 2 decibels. The relative thermal performance of some of these material will be discussed later.

Sterilization, Vacuum, Cold-Soak Tests

The sixteen materials selected for the sterilization, vacuum, and cold-soak testing are representative of several classes of ablation materials and included foamed and filled elastomers, Teflon, and filled epoxies and phenolics.

Figure 5 shows the sterilization, vacuum, and cold soak test sequence being used. Materials are sterilized for 92 hours at 135°C in dry nitrogen at atmospheric pressure. This is followed by 28 hours at 50°C in an atmosphere of 12% ethylene oxide, 88% Freon-12 at 50% relative humidity. The materials are then subjected on an acelerated vacuum exposure by exposing them for two weeks at 65°C at a pressure of 10^{-5} to 16^{-6} N/m^2. Materials are maintained in the vacuum and the temperature lowered to -73, -100, and -130°C. At each of these temperatures, bending tests are run on the material samples. The materials are deflected an amount that produces a strain approximately that expected due to the differential thermal contraction between the heat-shield material and a metallic substrate.

A summary of the test results is shown in table 3. Materials were tested as received at the three temperatures. Note that most of the materials can withstand the -100°C temperature without experiencing failure; however, about half do fail when the temperature is lowered to -130°C. The sterilization and vacuum appear to produce more failures only at the lowest test temperature. A few of the materials noted by the NT on the table have not completed their test cycle. Moduli of elasticity and rupture in bending measured before and after the environmental exposures indicates that the mechanical properties are slightly degraded by the sterilization and vacuum exposure. Based on these tests, it appears that the heat-shield temperature should be limited to -100°C or above to avoid the possibility of brittle cracking. This limitation does not appear to impose a severe restriction on planetary vehicle thermal control.

Ablation Tests of Low Density Materials

It has been generally observed that most ablation materials become less efficient as the heating-rate decreases. For conditions typical of a Mars entry, however, this trend can be offset by lowering material density, for it is also noted that the efficiency increases as the material density decreases.

Figure 6 shows the results of some tests conducted at the Langley Research Center and reported in reference 2 on a Langley formulated filled silicone elastomer. The ratio between the silicone resin and a low-density filler was varied to produce the density variation. The ordinate has been normalized to the efficiency of a filled silicone elastomer, designated Langley E4A1 and commonly called Purple Blend, which has a density of abour 640 kg/m^3 and is considered to have a relatively good thermal performance for materials in that density range. The figure shows that the performance of the low-density materials increases considerably as the density is reduced. For a particular entry environment, there is a practical lower density limit below which a material begins to experience mechanical failure and has inherent handling problems. For the Mars-entry environment, this density appears to lie between 200 and 250 kilograms per cubic meter.

Major aerospace companies have responded to the new materials requirements for a Mars mission by developing materials with densities less than 350 kilograms per cubic meter. A simplified description of these materials would be lightweight ablative-insulators. Most of the materials included in the previous two test programs were of higher density than that presently known to be more advantageous for the Mars-entry environment, but most low-density materials were still in the early stages of development at the time those programs were initiated. As part of the evaluation of some of the newer low-density materials, arc-jet ablation tests were recently performed at the Langley Research Center on nine low-density materials and E4A1, the 640 kg/m^3 filled silicone elastomer used as a reference for figure 6. The model configuration used is shown in figure 7 and the test conditions are given in table 4. Figure 8 shows the temperature rise measured by the copper calorimeter for two test conditions. The lower part of each bar indicates the temperature measured at the end of the heating period. The top of the shaded bands indicates the maximum temperature rise measured. For both the high heating-rate and low heating-rate tests, the material mass per unit area in front of the calorimeter was the same. The exposure time at each of the heating rates was such that the total heat load for each of the tests also was approximately the same. All of the materials tested had densities less than 320 kilograms per cubic meter with the exception of material C which is the Langley-filled-silicone elastomer with a density approximately twice that of any of the other materials. Again, the effect of the lower density can be seen. Materials W and X, although they are low-density materials, have a very high permeability. Recent studies at Langley Research Center have shown that high permeability together with a small model size can increase the severity of the effective heating environment and, therefore, may have a detrimental effect on the material's performance. Because of this, the results obtained here for materials W and X are not conclusive.

Although the test programs described thus far have not included all of the same materials, some of the materials included in the RF transmission and the recent ablation tests were the same. Comparative RF transmission and ablative performance for these materials is shown in figure 9. At the top of the figure, the RF transmission loss measured on the charred material at the low-heating-rate is again shown for material B, a low-density cork filled elastomer; material C, the high-density Langley elastomer; and material D, a low-density silicone ablator with only silica fillers. At the bottom, their relative ablative perfcrmance is shown along with that of material Z. Note that material D is not one of the best thermal performers. Material Z is comparable to material B in performance and is similar to C in composition. Such a material may offer a suitable compromise between RF transmission and ablative performance and, therefore, will be evaluated further in subsequent tests.

CONCLUDING REMARKS

In summary, a number of materials have been developed that appear to meet the primary requirements for use on a Mars-entry capsule. The RF transmission loss of heat-shield materials following exposure to a simulated entry environment was found to be high for all but a few materials, and those materials with an acceptable transmission loss did not have a high thermal efficiency. Based on limited test results, sterilization and long-time vacuum exposure do not significantly affect the flexibility of most heat shield materials at temperatures above -100°C. Some materials with densities between about 240 and 320 kilograms per cubic meter show good thermal shield capability in a simulated Mars-entry environment.

The need for further development of materials with good RF transparency together with high thermal efficiency is indicated.

REFERENCES

1. Supporting Research and Advanced Development, JPL Space Programs Summary 37-44, Vol. IV. April 30, 1967, pp. 73-75.

2. Moss, James N. and Howell, William E.: Recent Developments in Low Density Ablators. Paper presented to 12th National SAMPE Symposium, Oct. 10-12, 1967.

Table 1.– Description of materials tested.

Material Designation	Density, kg/m^3	Resin or binder	Fillers[a]
A	510	silicone	cork, glass fibers
B	240	silicone	cork, hollow microspheres, fibers
C	640	silicone	hollow phenolic and silica microspheres, quartz fibers (Langley E4A1)
D	240	silicone	hollow silica microspheres, fibers
E	680	silicone	hollow glass and phenolic microspheres, quartz fibers
F	400	silicone	hollow microspheres (foamed)
G	320	nitrile rubber	(foamed)
H	750	Teflon	(foamed)
J	380	epoxy	hollow microspheres, glass fibers
K	530	epoxy	hollow microspheres, glass fibers (material for RF transmission specimen was in 0.95 cm (3/8 in.) cell phenolic–glass honeycomb)
L	610	silicone–phenolic	phenolic microspheres (Langley E6A7)
M	480	silicone	(foamed)
N	320	silicone	(foamed – same composition as M)
P	600	silicone	
Q	680	silicone	hollow glass and phenolic microspheres, quartz fibers
R	680	silicone	cork, hollow glass microspheres, quartz fibers
S	540	Teflon	(foamed)
T	580	phenolic	phenolic microspheres, nylon powder
U	310	silicone	phenolic microspheres, quartz fibers, nylon powder
V	310	silicone	phenolic microspheres, quartz fibers, nylon powder
W	240	silicone	(foamed – same composition as M)
X	240	silicone	(foamed)
Y	230	silicone–epoxy	(foamed)
Z	240	silicone	phenolic microspheres, quartz fibers

[a] Most materials listed are proprietary compositions. The fillers listed were determined from visual observation. The materials may contain other unknown ingredients.

Table 2.– Nominal test conditions for RF transmission tests

Test condition	Test 1	Test 2
Heat–transfer rate at center of panel, kW/m^2	240	840
Total enthalpy, MJ/kg	6.5	6.3
Mach number	3.4	3.5
Free–stream velocity, km/s	2.95	2.93
Model stagnation pressure, atmospheres	0.15	0.17
Static pressure at center of panel, atmospheres	0.015	0.11
Mass–flow rate, kg/s	0.136	0.158
Test stream composition	Air	Air
Model exposure time, s	60	30
Transmitter frequency, GHz	35	35

Table 3.– Effect of Sterilization, Vacuum, and Cold–Soak on Material Flexibility

MATERIAL TYPE	CODE	AS RECEIVED			AFTER STERILIZATION AND VACUUM		
		–73°C	–100°C	–130°C	-73°C	–100°C	–130°C
FILLED SILICONE ELASTOMERS	A	NF	NF	00000	NT	–	–
	B			XXXXX	NF	NF	XXXXX
	E			X000			XXX
	P			00000			XXX00
	Q			XXXX			XXXXX
	R			XXXXX			XXXXX
	F			XXXX			XXXXX
FOAMED MATERIALS	G			XXXX0	NT	–	–
	M			0000	NF	NF	00000
	N			X000	NF	NF	X0000
TEFLON	H			0000	NT	–	–
	S			00000	NT	–	–
FILLED EPOXY	J			XXXXX	NF	NF	XX00
	K			00000	NF		00000*
FILLED PHENOLIC	L	X		XX	X		XX
	T	NF	XXX	XX	NF	X	0000*

0 Denotes specimens that did not fail at lowest temperature
X Denotes specimens failed
* Not deflected full value
NF No failure
NT Not tested

Table 4.– Nominal test conditions for ablative tests

Test condition	Test 1	Test 2
Stagnation point heat–transfer rate, kW/m^2	170	570
Total enthalpy, MJ/kg	3.0	7.0
Mach number	4.0	3.8
Free–stream velocity, km/s	2.06	2.98
Model stagnation pressure, atmospheres	0.023	0.052
Mass–flow rate, kg/s	0.023	0.045
Test stream composition	Air	Air
Model exposure time, s	100	30

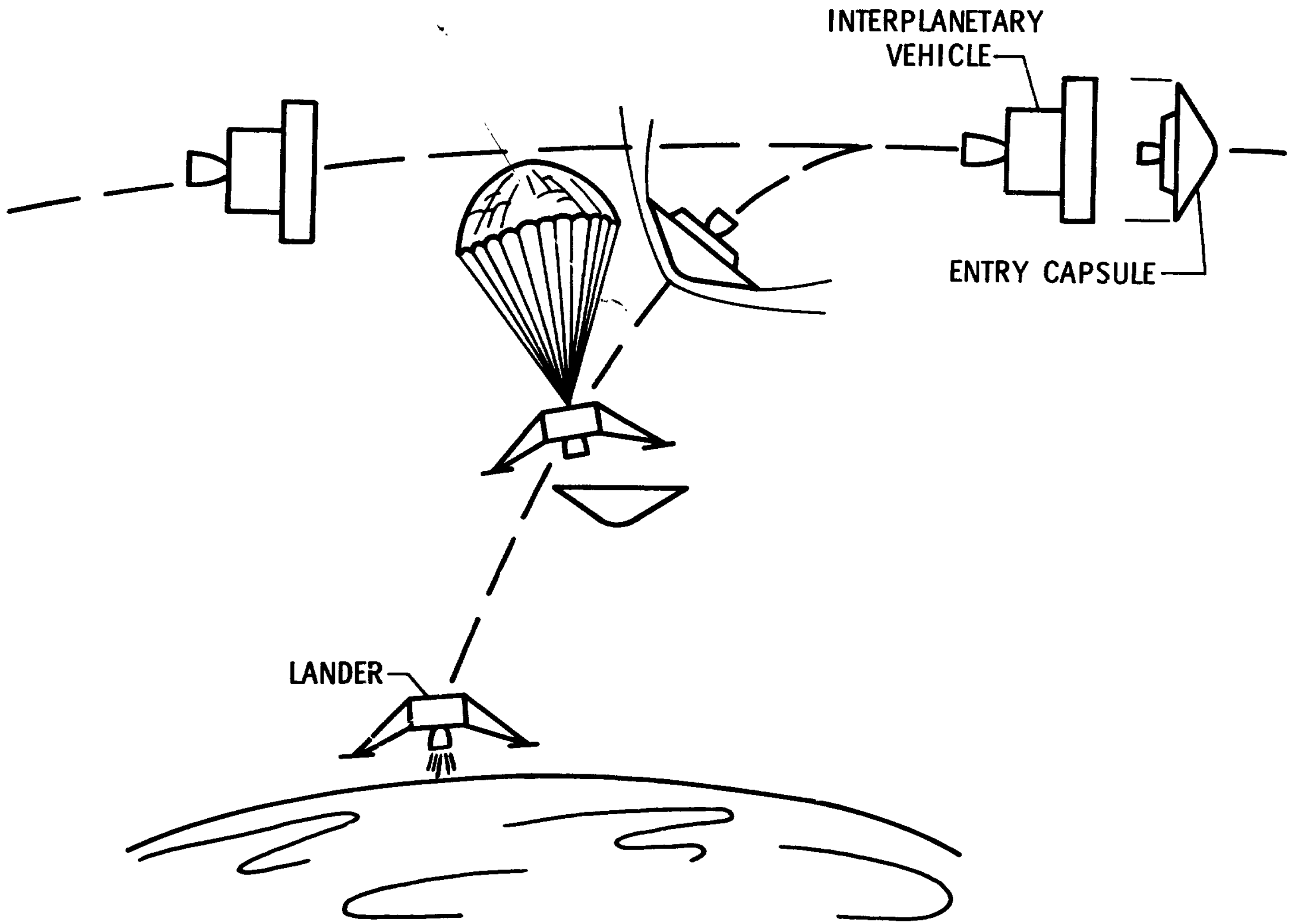

Figure 1.- Entry sequence for Mars-entry vehicle.

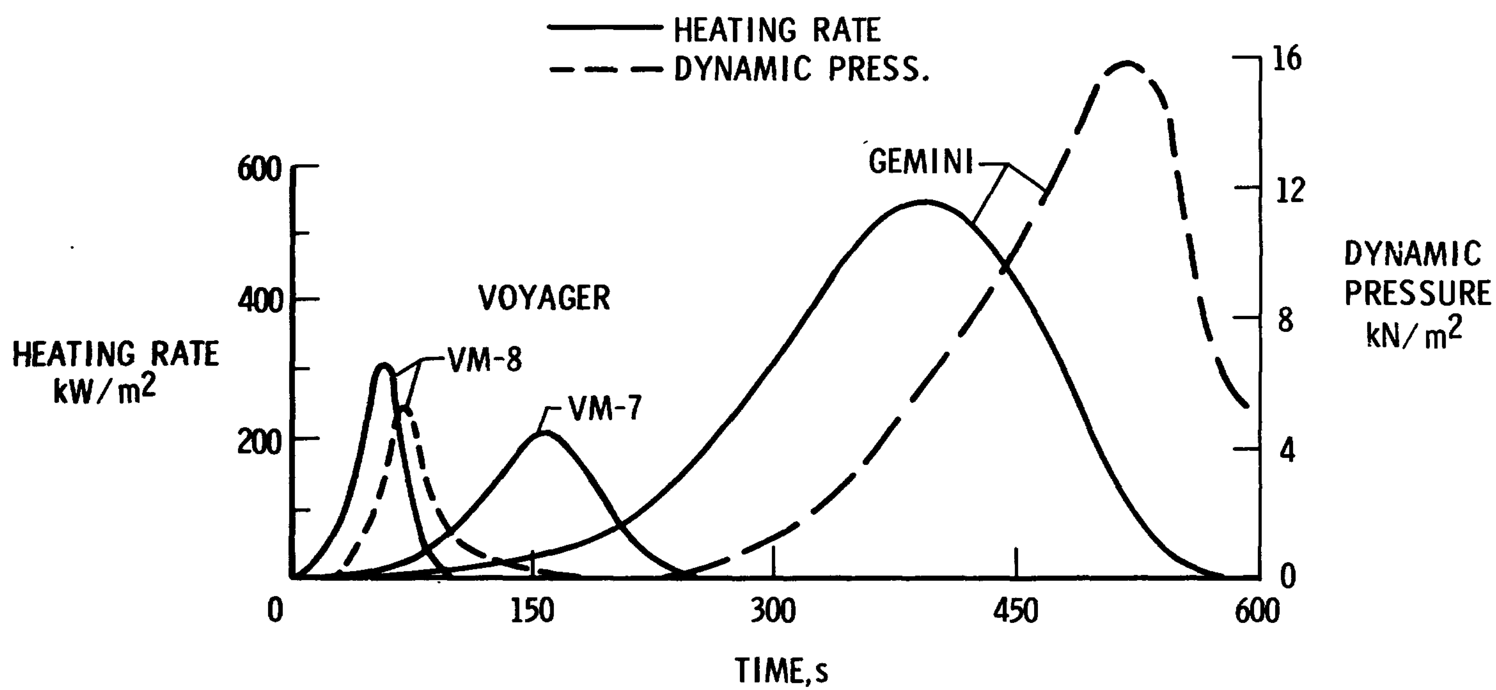

Figure 2.- Heating rate and dynamic pressure for Gemini and Voyager vehicles. (Voyager vehicle assumed to have a 0.7 m nose radius.)

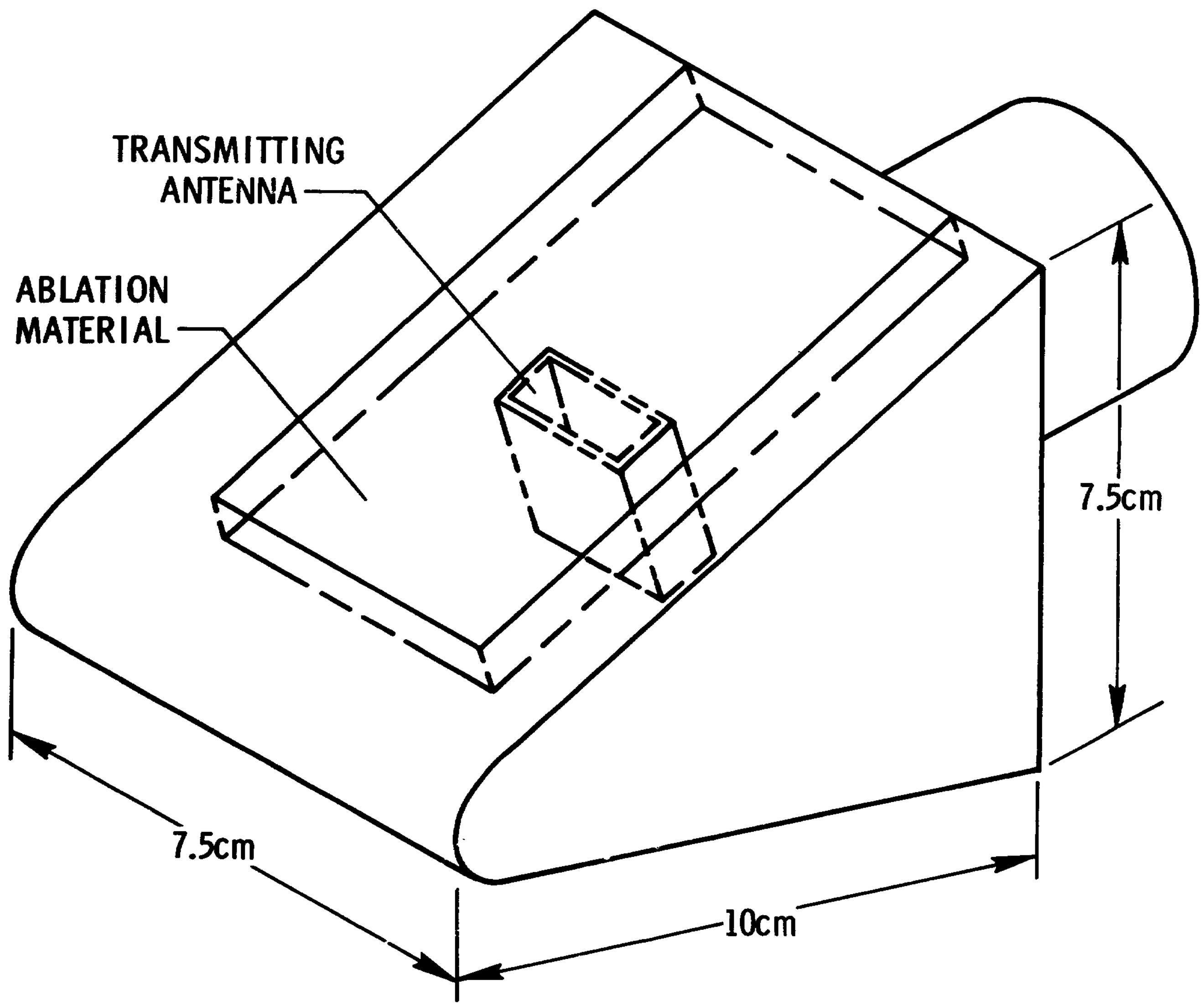

Figure 3.- RF transmission test model.

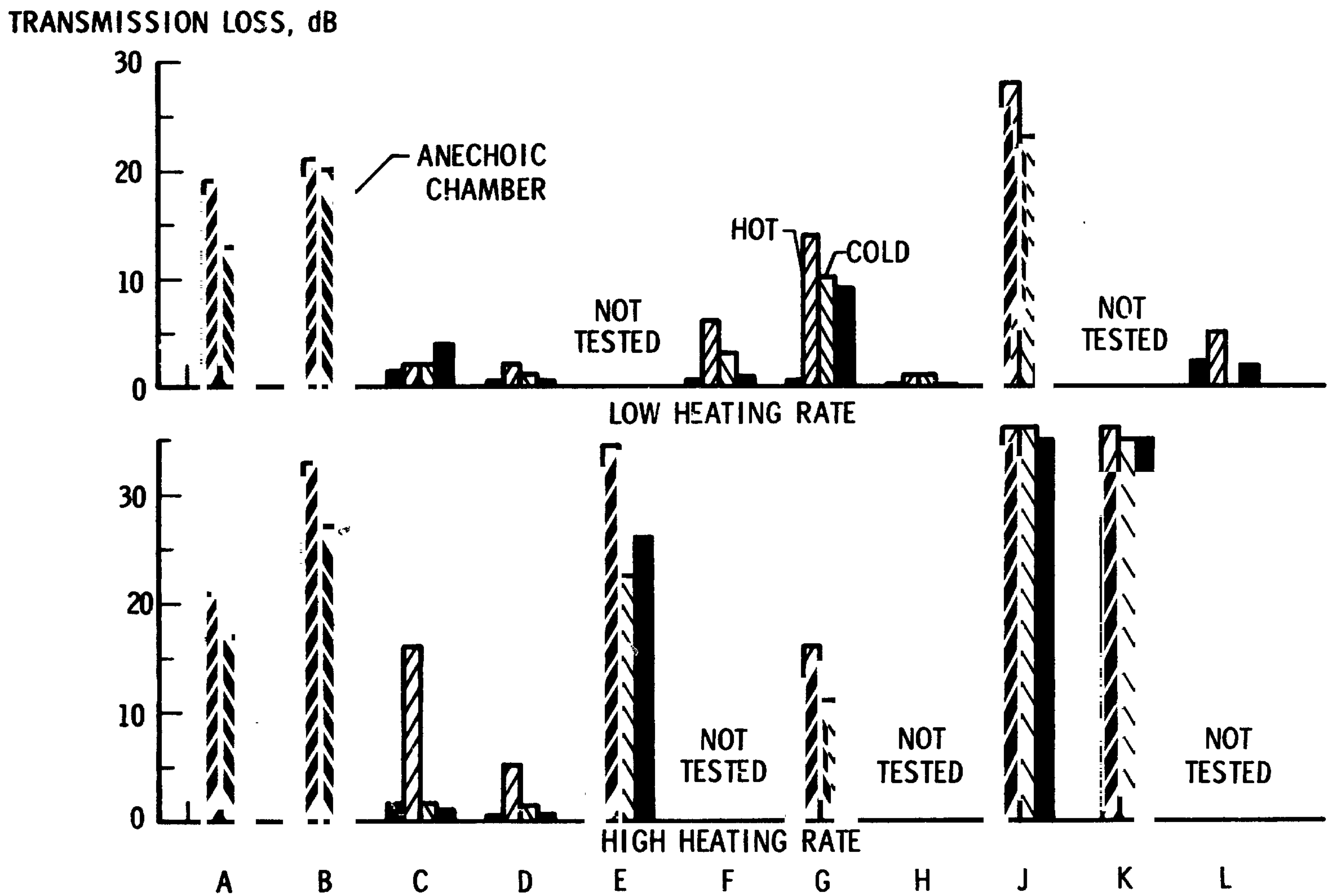

Figure 4.- RF transmission loss through ablative materials.

STERILIZATION		
92 HOURS	135^0 C	DRY NITROGEN
28 HOURS	50^0 C	ETO-FREON 12
ACCELERATED VACUUM EXPOSURE		
2 WEEKS	65^0 C	10^{-5} TO 10^{-6} N/m^2
COLD SOAK - FLEXURE TEST		
	-73^0 C -100^0 C -130^0 C	10^{-5} TO 10^{-6} N/m^2

Figure 5.- Sterilization, vacuum, and cold-soak test sequence.

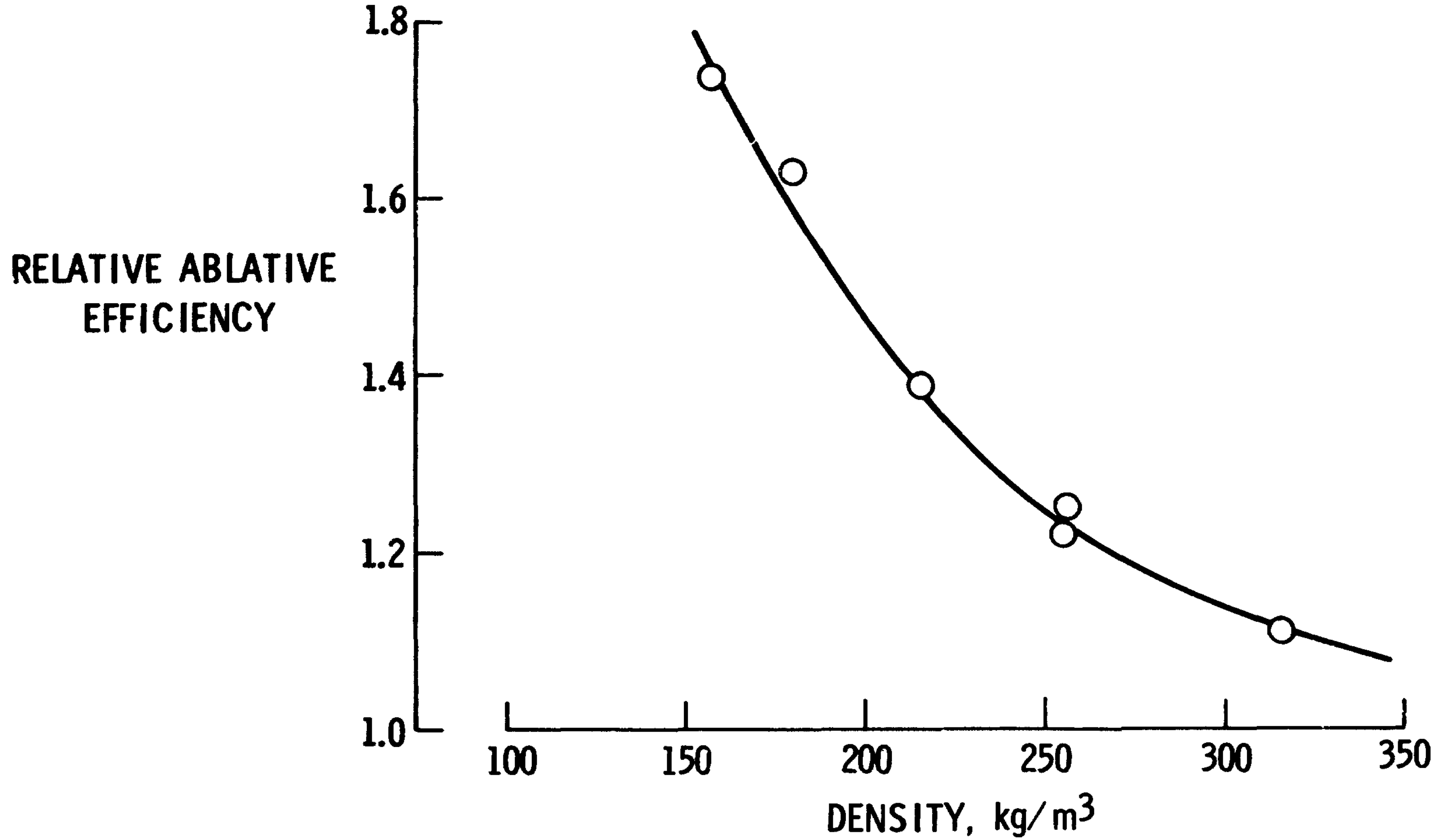

Figure 6.- Effect of density on ablative efficiency of filled silicone elastomer.

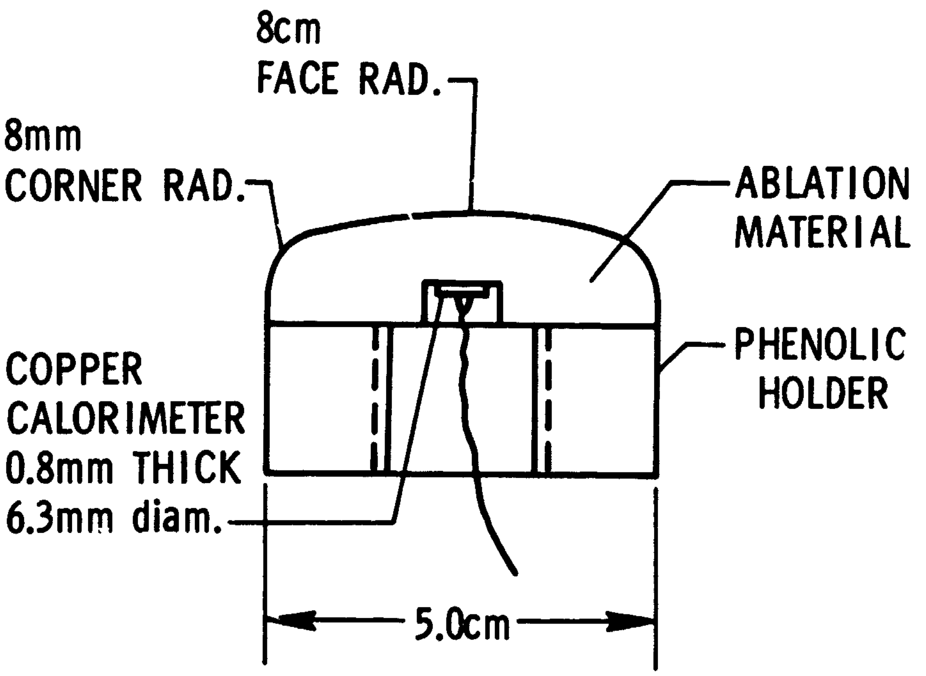

Figure 7.- Ablation model configuration.

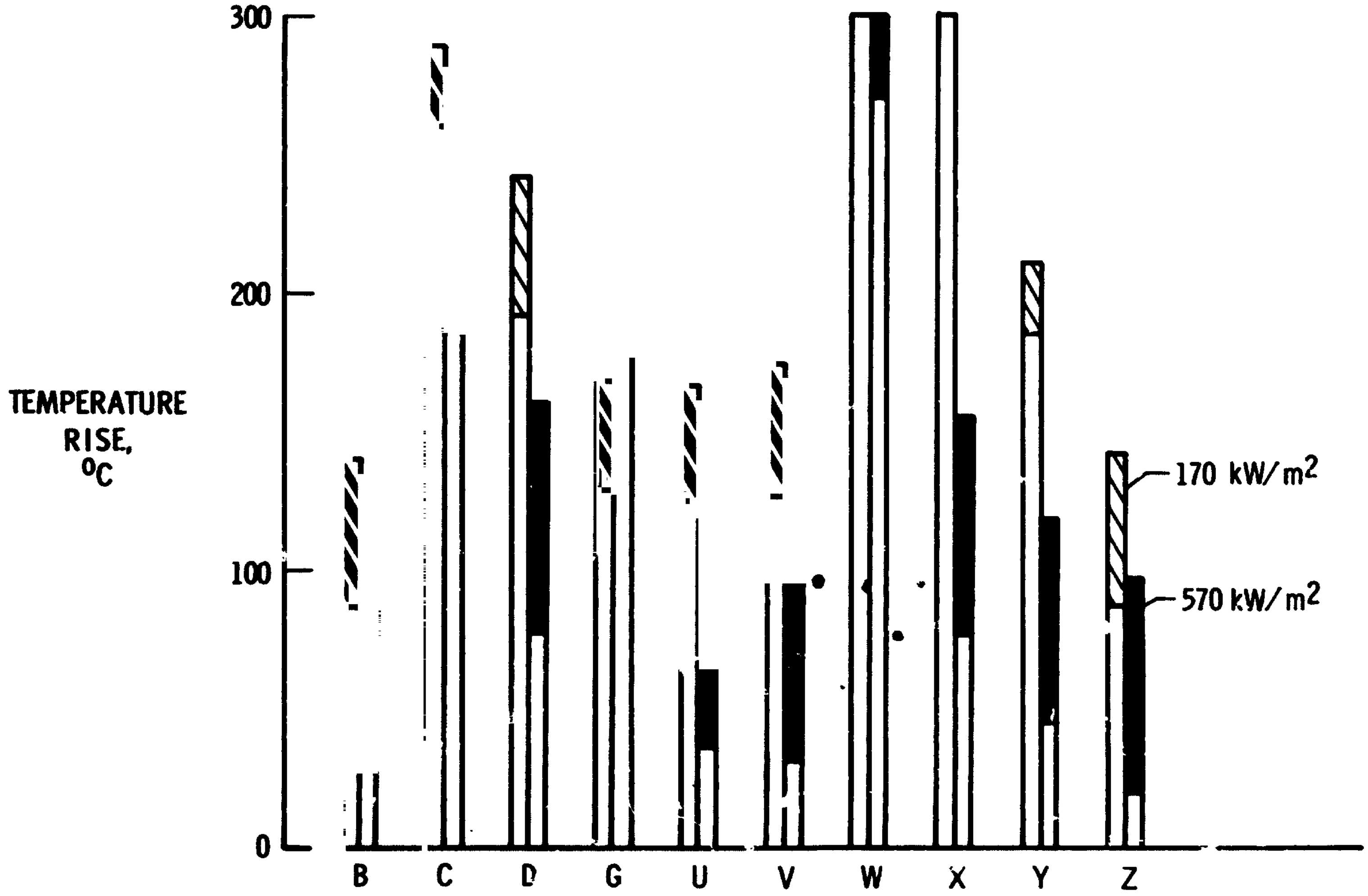

Figure 8.- Relative thermal performance of low-density materials.

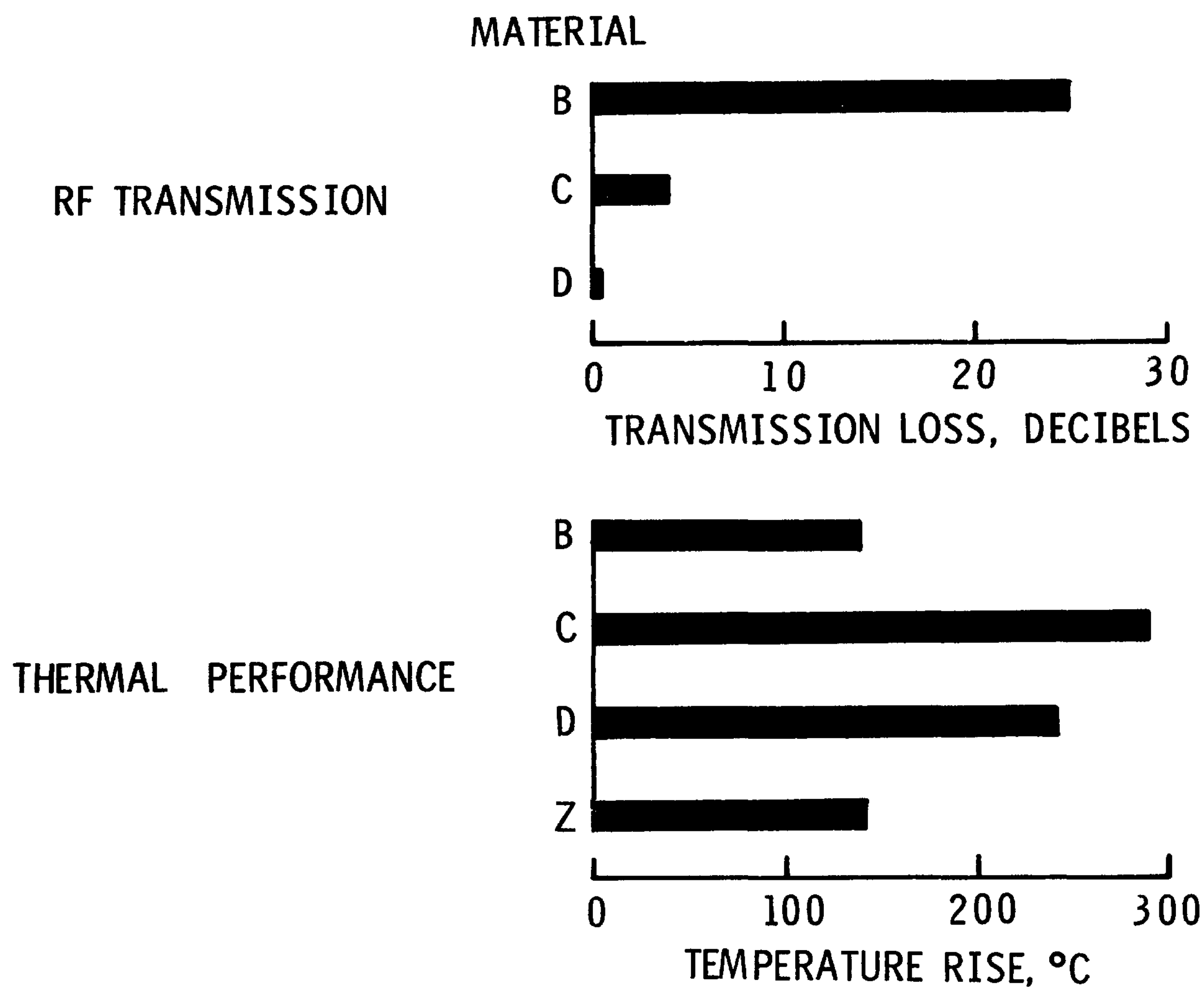

Figure 9.- Comparison of RF transmission and thermal performance.

NASA-Langley, 1967